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(54) **DEVICES AND METHODOLOGIES RELATED TO STRUCTURES HAVING HBT AND FET**

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See application file for complete search history.

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(56) **References Cited**

U.S. PATENT DOCUMENTS

5,445,976 A * 8/1995 Henderson et al. 438/319
6,906,359 B2 6/2005 Zampardi et al.

(Continued)

FOREIGN PATENT DOCUMENTS

KR 10-2006-0064688 A 6/2006
TW 201232715 8/2012

(Continued)

OTHER PUBLICATIONS

International Search Report and Written Opinion issued on Jun. 29, 2012 in connection with related PCT Application No. PCT/US2011/059208.

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H01L 27/06 (2006.01)

H01L 29/737 (2006.01)

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(52) **U.S. Cl.**

CPC **H01L 27/0623** (2013.01); **H01L 29/66318** (2013.01); **H01L 29/66462** (2013.01); **H01L 29/7371** (2013.01); **H01L 29/812** (2013.01)

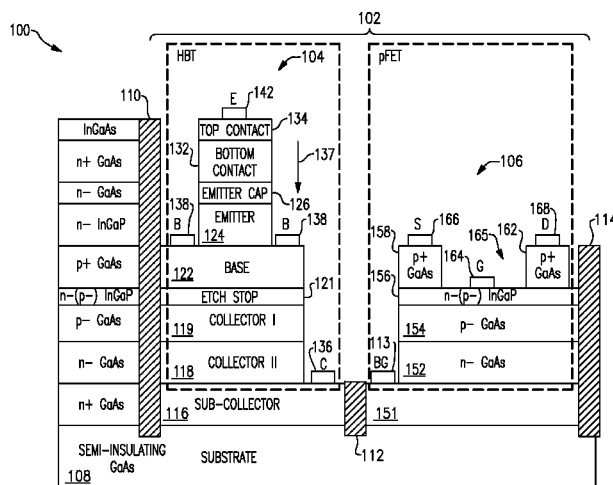
(58) **Field of Classification Search**

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(57) **ABSTRACT**

A semiconductor structure includes a heterojunction bipolar transistor (HBT) including a collector layer located over a substrate, the collector layer including a semiconductor material, and a field effect transistor (FET) located over the substrate, the FET having a channel formed in the semiconductor material that forms the collector layer of the HBT. In some implementations, a second FET can be provided so as to be located over the substrate and configured to include a channel formed in a semiconductor material that forms an emitter of the HBT. One or more of the foregoing features can be implemented in devices such as a die, a packaged module, and a wireless device.

34 Claims, 6 Drawing Sheets



US 9,105,488 B2

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(56)

References Cited

U.S. PATENT DOCUMENTS

2003/0116782 A1 6/2003 Mizutani
2005/0139921 A1* 6/2005 Kang et al. 257/347
2006/0249752 A1 11/2006 Asano
2008/0296624 A1 12/2008 Murayama et al.
2009/0289279 A1 11/2009 Khare

2010/0001319 A1* 1/2010 Pelouard et al. 257/197
2010/0072517 A1 3/2010 Zampardi et al.

FOREIGN PATENT DOCUMENTS

WO WO 2009-040509 4/2009
WO WO 2012/061632 5/2012

* cited by examiner

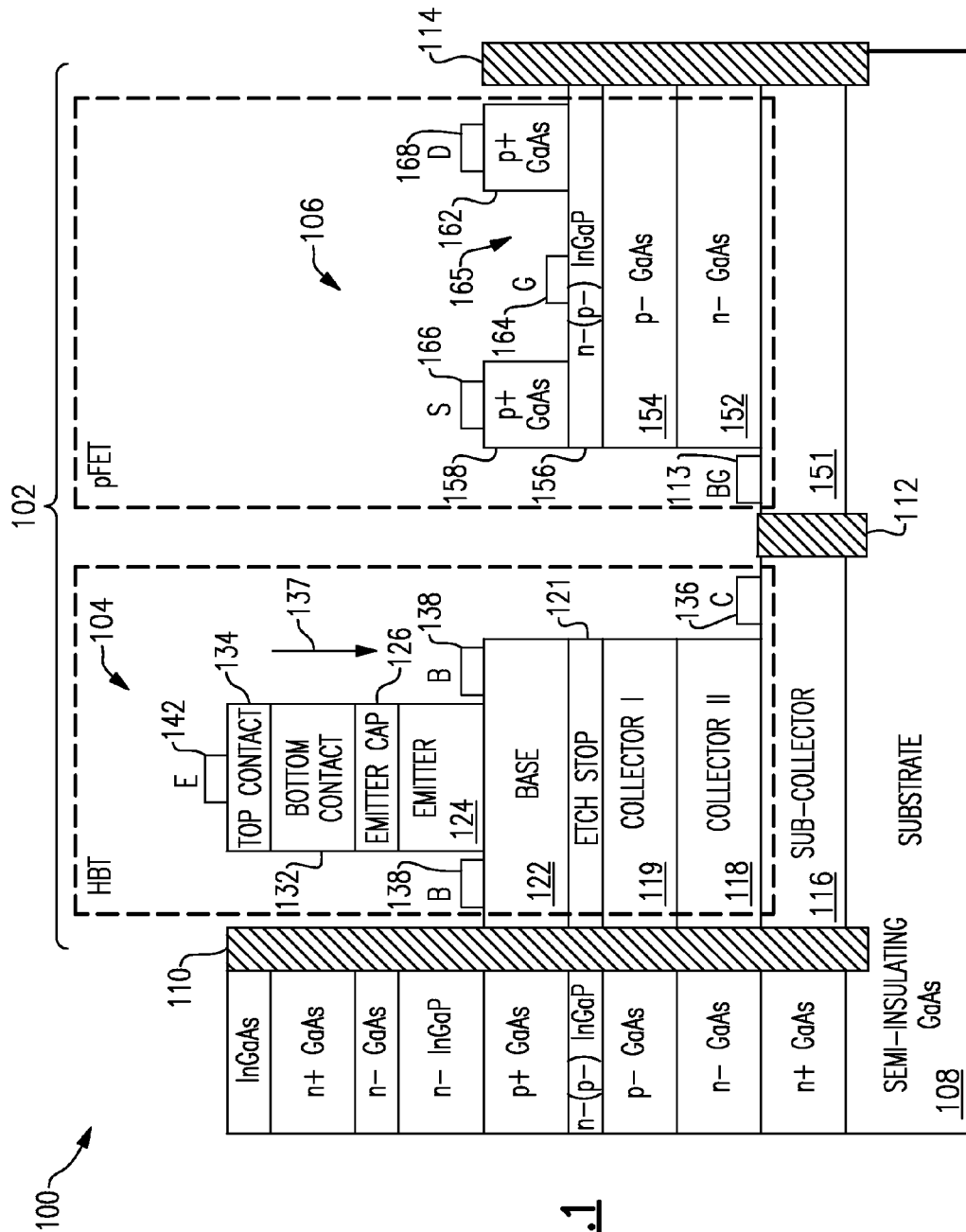


FIG.1

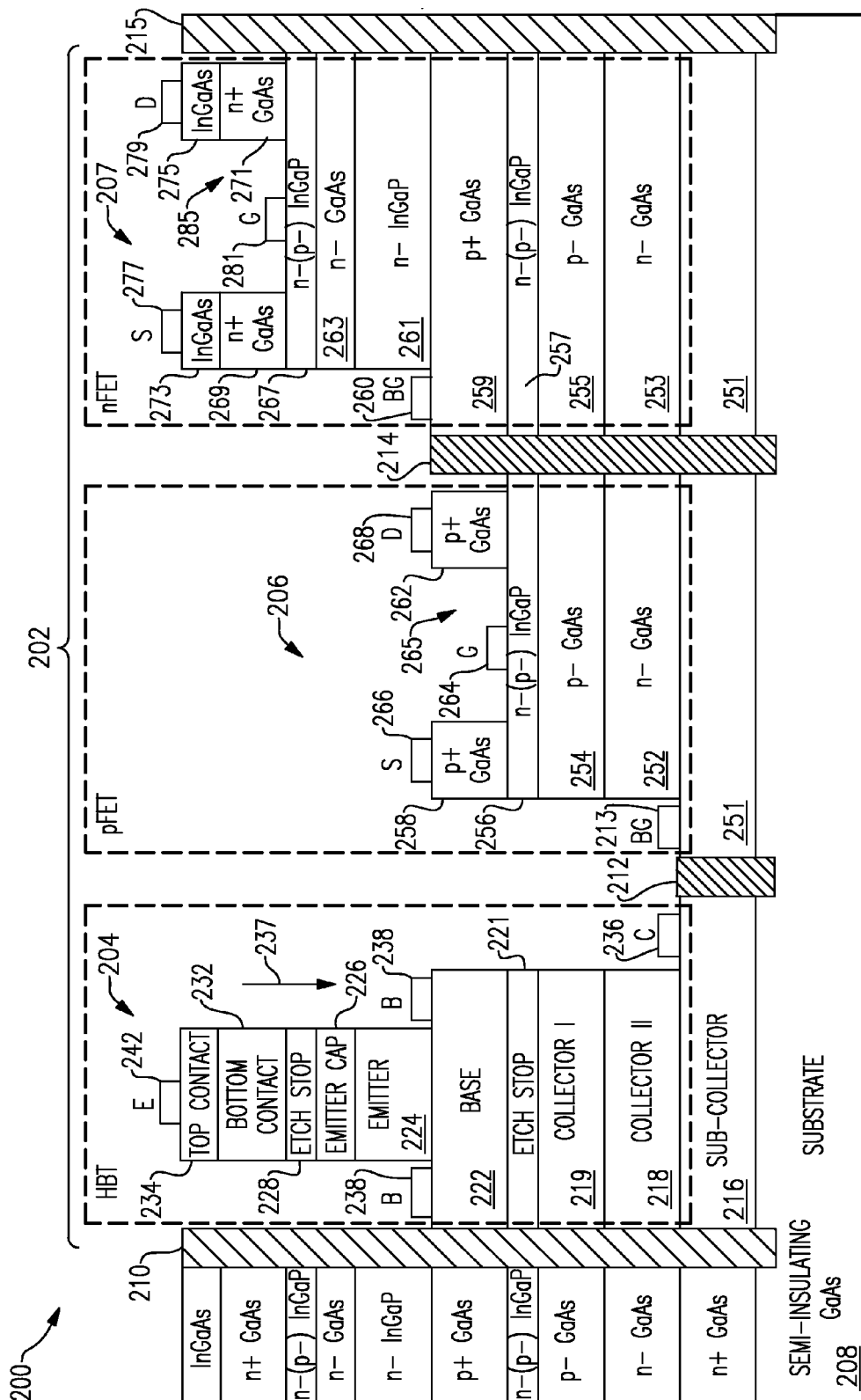
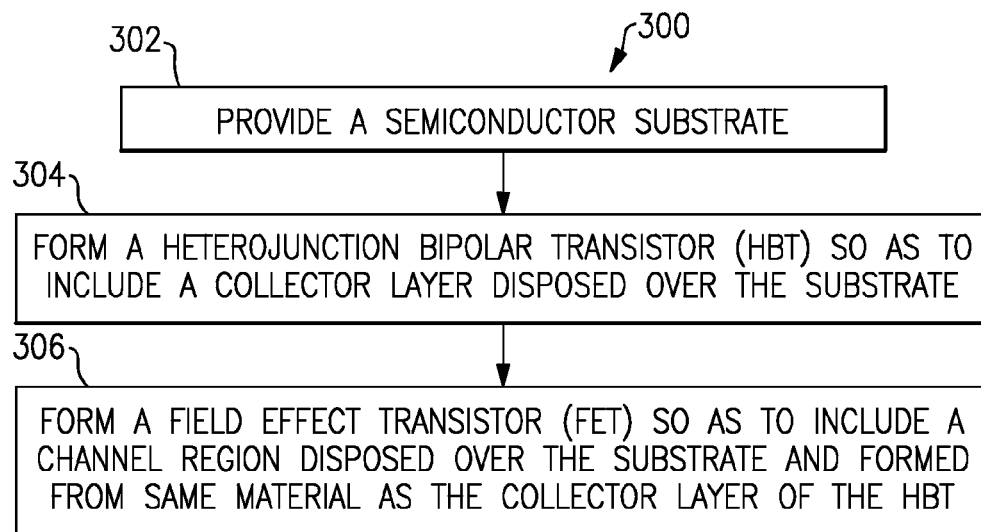
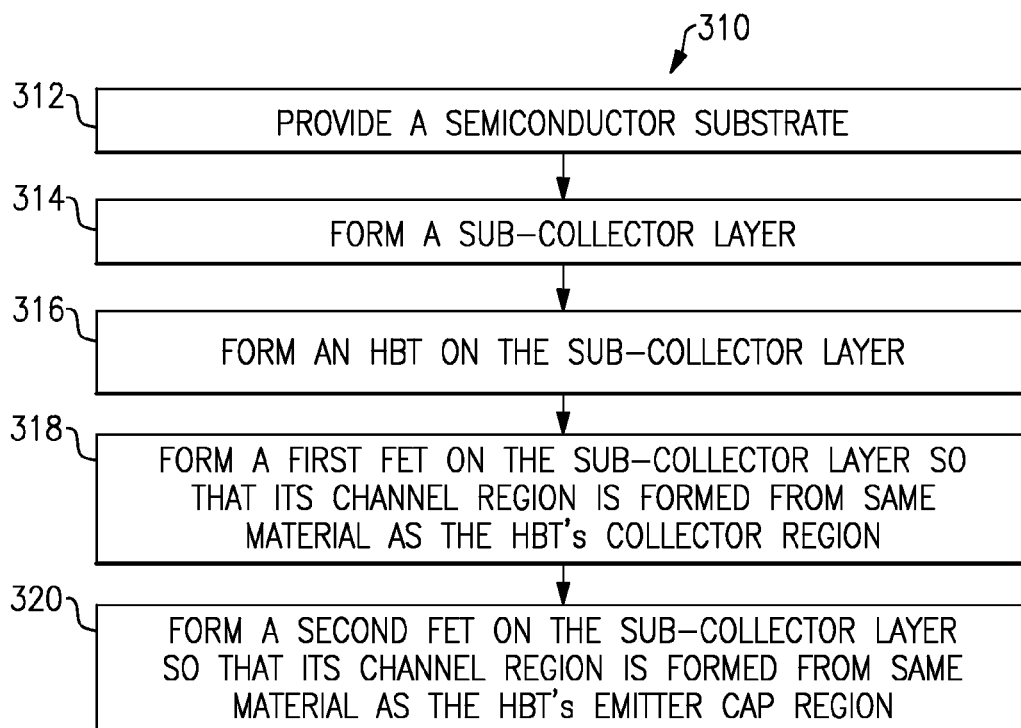


FIG.2

**FIG.3****FIG.4**

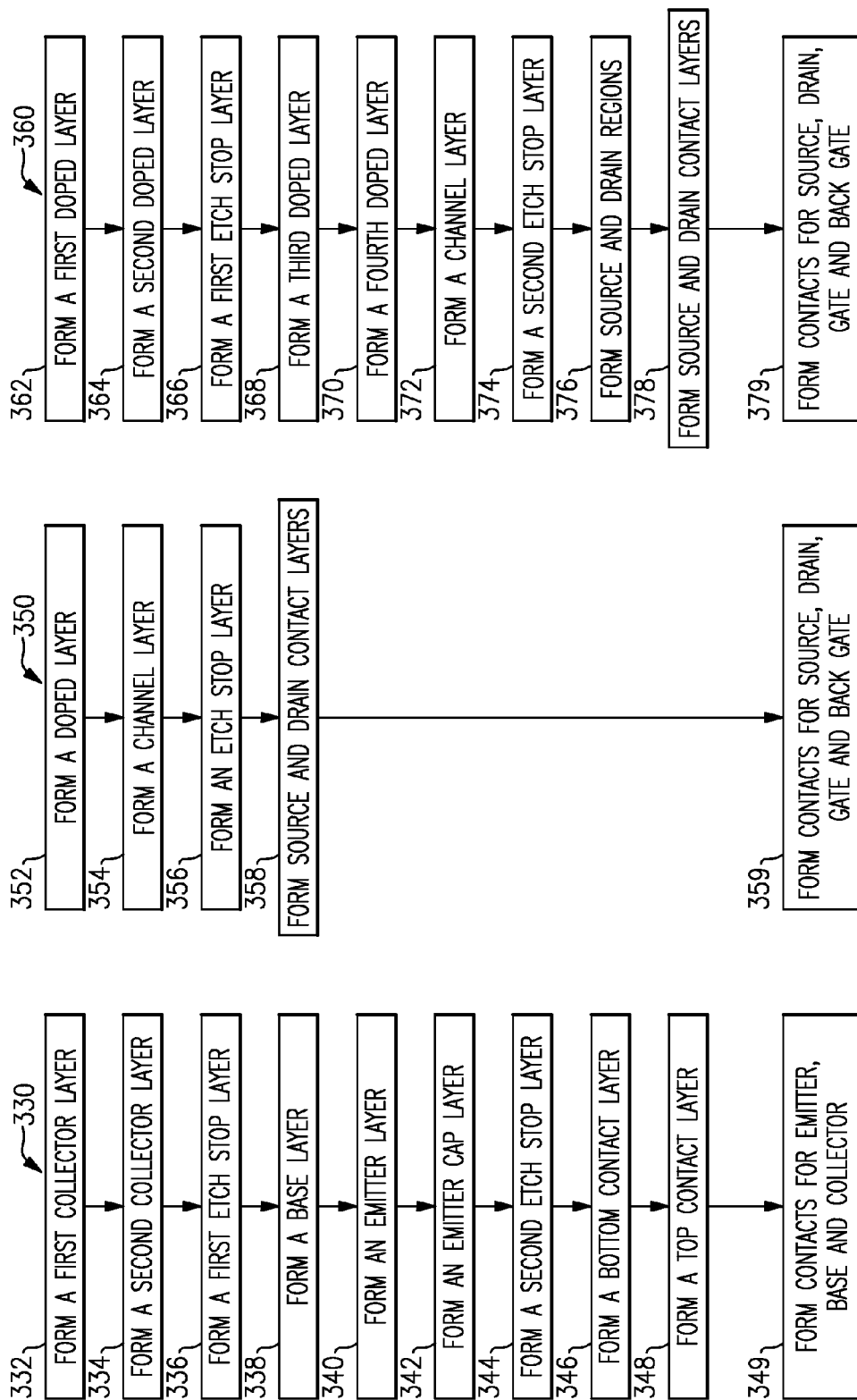
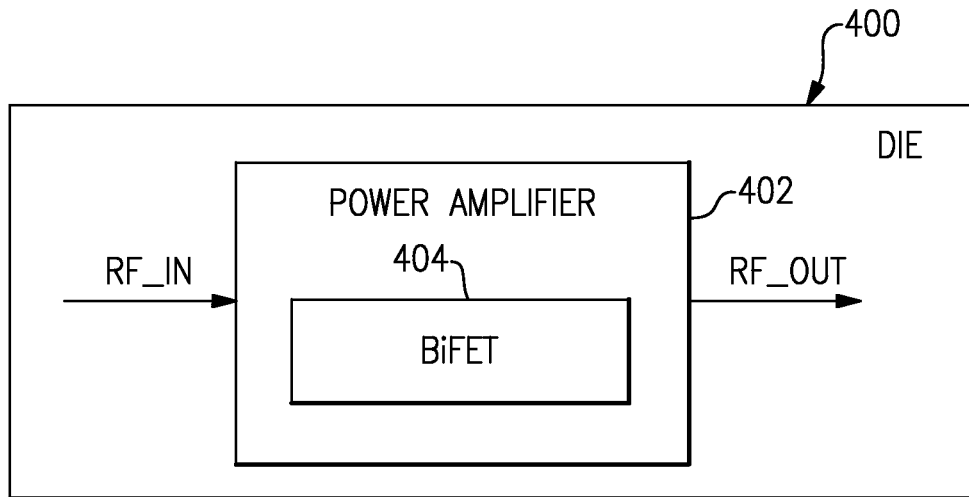
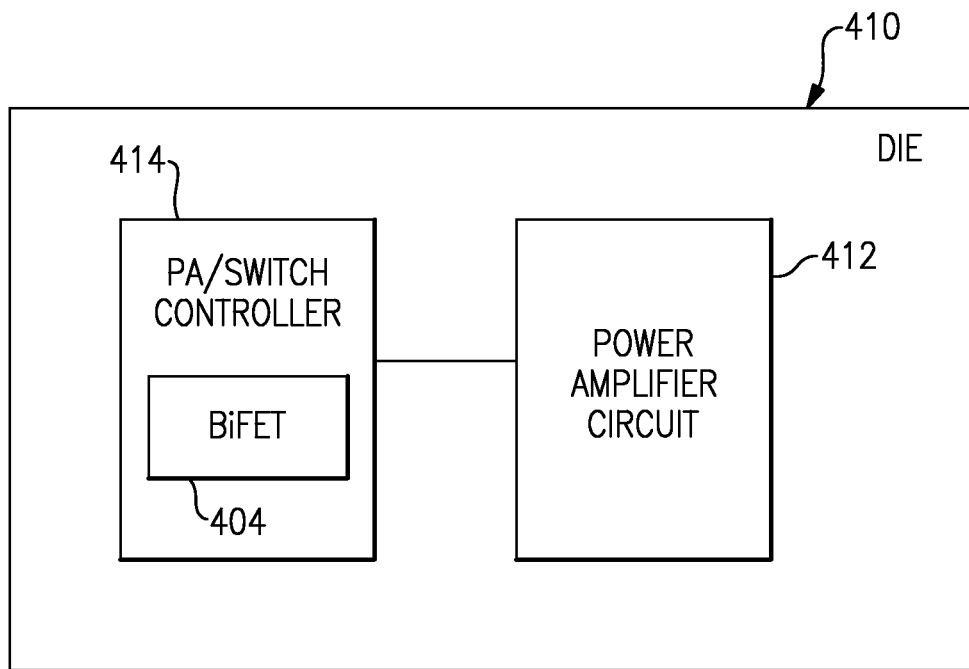
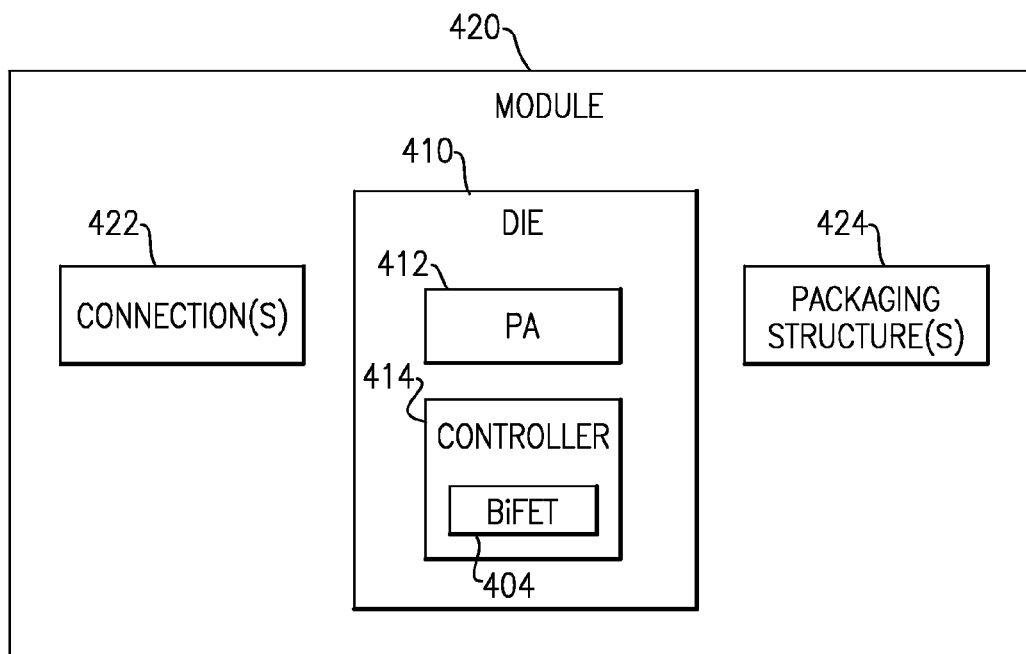
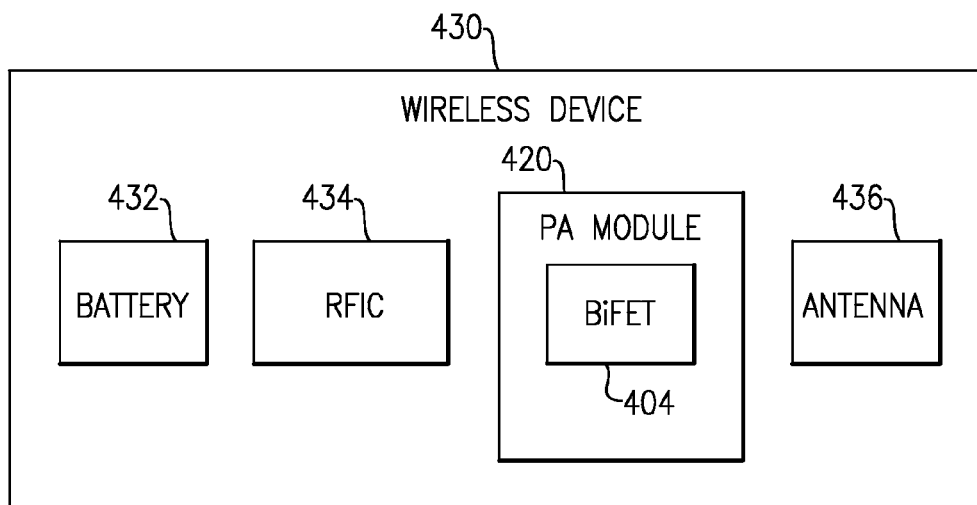


FIG. 5

FIG. 6

FIG. 7

FIG.8FIG.9

**FIG.10****FIG.11**

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DEVICES AND METHODOLOGIES RELATED TO STRUCTURES HAVING HBT AND FET

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 12/939,474, filed on Nov. 4, 2010, entitled "BIPOLAR AND FED DEVICE STRUCTURE," the benefits of the filing date of which is hereby claimed and the specification of which is incorporated herein by this reference.

BACKGROUND

In some semiconductor material systems it is possible to combine different device technologies on a single semiconductor die to form hybrid structures. For example, in certain material systems, it is possible to integrate a heterojunction bipolar transistor (HBT) with a field effect transistors (FET) on a single substrate, to fabricate what is referred to as a BiFET. Devices, such as RF power amplifiers, can be fabricated using BiFET technology to have increased design flexibility. As a result, a BiFET power amplifier including an HBT and a FET can be advantageously designed to operate at a lower reference voltage than a bipolar transistor power amplifier. Of particular interest to device manufacturers are high power BiFET amplifiers, which can be formed by integrating a FET into a gallium arsenide (GaAs) HBT process. However, previous attempts to integrate a FET into a GaAs HBT process have resulted only in an n-type FET device.

Therefore, it would be desirable to have a BiFET device structure that includes a p-type FET device, and that may include complementary n-type and p-type FET devices.

SUMMARY

Embodiments of a semiconductor structure include a heterojunction bipolar transistor (HBT) including a collector layer located over a substrate, the collector layer comprising a semiconductor material, and a field effect transistor (FET) located over the substrate, the FET comprising a channel formed in the semiconductor material that forms the collector layer of the HBT.

In some embodiments, the semiconductor material that forms the collector layer of the HBT and the channel of the FET can include p-type gallium arsenide. In some embodiments, the semiconductor structure can further include an etch stop layer segment located over the collector layer of the HBT and the channel of the FET. In some embodiments, such an etch stop layer can include indium gallium arsenide (InGaAs) or indium gallium phosphide (InGaP), and can have a thickness range between 10 nanometers (nm) and 15 nm. Other thickness ranges can also be implemented. In some embodiments, such an etch stop layer can include any material with etch selectivity to, for example, the channel layer of the FET. Such a material can be implemented in an appropriate thickness or within an appropriate range of thicknesses so as to achieve similar results as the foregoing example materials InGaAs or InGaP.

In accordance with some embodiments, the present disclosure relates to a semiconductor structure having a heterojunction bipolar transistor (HBT) that includes a collector layer located over a substrate and an emitter layer located over the substrate. The collector layer includes a first semiconductor material of a first conductivity type (P), and the emitter layer includes a second semiconductor material of a second con-

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ductivity type (N). The semiconductor structure further includes a first field effect transistor (FET) located over the substrate. The first FET includes a channel formed in the first semiconductor material that forms the collector layer of the HBT. The semiconductor structure further includes a second field effect transistor (FET) located over the substrate. The second FET includes a channel formed in the second semiconductor material that forms the emitter layer of the HBT.

In some embodiments, the first semiconductor material that forms the collector layer of the HBT and the channel of the first FET can include p-type gallium arsenide, and the second semiconductor material that forms the emitter layer of the HBT and the channel of the second FET can include n-type gallium arsenide. In some embodiments, semiconductor structure can further include a first etch stop layer segment located over the collector layer of the HBT and the channel of the first FET, and a second etch stop layer segment located over the emitter layer of the HBT and the channel of the second FET. The first etch stop layer segment and the second etch stop layer segment can include indium gallium arsenide (InGaAs) or indium gallium phosphide (InGaP), and can have a thickness range between 10 nanometers (nm) and 15 nm. Other thickness ranges can also be implemented. In some embodiments, such etch stop layers can include any material with etch selectivity to, for example, the channel layers of the first and second FETs. Such a material can be implemented in an appropriate thickness or within an appropriate range of thicknesses so as to achieve similar results as the foregoing example materials InGaAs or InGaP.

In a number of implementations, the present disclosure relates to a method that includes forming a heterojunction bipolar transistor (HBT) including a collector layer located over a substrate and an emitter layer located over the substrate. The collector layer includes a first semiconductor material of a first conductivity type (P), and the emitter layer includes a second semiconductor material of a second conductivity type (N). The method further includes forming a first field effect transistor (FET) over the substrate. The first FET includes a channel formed in the first semiconductor material that forms the collector layer of the HBT. The method further includes forming a second field effect transistor (FET) over the substrate. The second FET includes a channel formed in the second semiconductor material that forms the emitter layer of the HBT.

In some implementations, the first semiconductor material that forms the collector layer of the HBT and the channel of the first FET can include p-type gallium arsenide, and the second semiconductor material that forms the emitter layer of the HBT and the channel of the second FET can include n-type gallium arsenide. In some implementations, the method can further include forming a first etch stop layer segment over the collector layer of the HBT and the channel of the first FET, and forming a second etch stop layer segment over the emitter layer of the HBT and the channel of the second FET. The first etch stop layer segment and the second etch stop layer segment can include indium gallium arsenide (InGaAs) or indium gallium phosphide (InGaP), and can have a thickness range between 10 nanometers (nm) and 15 nm.

According to some implementations, the present disclosure relates to a method that includes forming a heterojunction bipolar transistor (HBT) including a collector layer located over a substrate. The collector layer includes a semiconductor material. The method further includes forming a field effect transistor (FET) located over the substrate. The FET includes a channel formed in the semiconductor material that forms the collector layer of the HBT.

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In some implementations, the semiconductor material that forms the collector layer of the HBT and the channel of the FET can include p-type gallium arsenide. In some implementations, the method can further include forming an etch stop layer segment located over the collector layer of the HBT and the channel of the FET. The etch stop layer can include indium gallium arsenide (InGaAs) or indium gallium phosphide (InGaP), and can have a thickness range between 10 nanometers (nm) and 15 nm.

According to some embodiments, the present disclosure relates to a die having an integrated circuit (IC). The die includes a circuit configured to process radiofrequency (RF) signal. The die further includes an assembly of a heterojunction bipolar transistor (HBT) and a field effect transistor (FET) configured to facilitate operation of the circuit. The HBT includes a collector layer including a semiconductor material located over a substrate. The FET includes a channel located over the substrate and formed in the semiconductor material that forms the collector layer of the HBT.

In some embodiments, the circuit configured to process RF signal can include a power amplifier circuit, a controller circuit for the power amplifier circuit, or a controller for a switching circuit. In some embodiments, the assembly can further include a second FET having a channel located over the substrate and formed in same semiconductor material as an emitter of the HBT. The first FET can include a pFET, and the second FET can include an nFET. In some embodiments, the substrate can include gallium arsenide (GaAs).

In a number of embodiments, the present disclosure relates to a packaged module for a radiofrequency (RF) device. The module includes a packaging substrate and an integrated circuit (IC) formed on a die and mounted on the packaging substrate. The IC includes an assembly of a heterojunction bipolar transistor (HBT) and a field effect transistor (FET) configured to facilitate operation of the IC. The HBT includes a collector layer including a semiconductor material located over a die substrate. The FET includes a channel located over the die substrate and formed in the semiconductor material that forms the collector layer of the HBT. The module further includes one or more connections configured to facilitate transfer of power to the IC and RF signals to and from the IC.

In some embodiments, the assembly can further include a second FET having a channel located over the die substrate and formed in same semiconductor material as an emitter of the HBT. The first FET can include a pFET and the second FET can include an nFET.

In accordance with some embodiments, the present disclosure relates to a wireless device having an antenna and a radiofrequency integrated circuit (RFIC) configured to process RF signals received from the antenna and for transmission through the antenna. The wireless device further includes a power amplifier (PA) circuit configured to amplify the RF signals. The PA circuit includes an assembly of a heterojunction bipolar transistor (HBT) and a field effect transistor (FET). The HBT includes a collector layer including a semiconductor material located over a substrate. The FET includes a channel located over the substrate and formed in the semiconductor material that forms the collector layer of the HBT.

In some embodiments, the PA can be configured to operate as a high power BiFET amplifier capable of operating at a lower reference voltage than that of a bipolar transistor PA. In some embodiments, the substrate can include gallium arsenide (GaAs).

Other embodiments are also provided. Other systems, methods, features, and advantages of the invention will be or become apparent to one with skill in the art upon examination

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of the following figures and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE FIGURES

The invention can be better understood with reference to the following figures. The components within the figures are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the invention. Moreover, in the figures, like reference numerals designate corresponding parts throughout the different views.

FIG. 1 is a schematic diagram illustrating a cross-sectional view of an exemplary structure including an exemplary BiFET.

FIG. 2 is a schematic diagram illustrating a cross-sectional view of an alternative embodiment of the structure of FIG. 1.

FIG. 3 shows a process that can be implemented to fabricate the example structure of FIG. 1.

FIG. 4 shows a process that can be implemented to fabricate the example structure of FIG. 2.

FIG. 5 shows a process that can be implemented to fabricate the example HBTs of FIGS. 1 and 2.

FIG. 6 shows a process that can be implemented to fabricate the example FET of FIG. 1 and the first FET of FIG. 2.

FIG. 7 shows a process that can be implemented to fabricate the example second FET of FIG. 2.

FIG. 8 shows that in some embodiments, a semiconductor die having a circuit, such as a power amplifier (PA) circuit, can include a BiFET device having one or more features as described herein.

FIG. 9 shows that in some embodiments, a semiconductor die having a PA controller and/or a switch controller circuit can include a BiFET device having one or more features as described herein.

FIG. 10 shows that in some embodiments, a packaged module can include a die having one or more features as described herein.

FIG. 11 shows that in some embodiments, a wireless device can include a module, such as the packaged module FIG. 10, having one or more features as described herein.

DETAILED DESCRIPTION

Although described with particular reference to a device fabricated in the gallium arsenide (GaAs) material system, the structures described herein can be fabricated using other III-V semiconductor materials, such as indium phosphide (InP) and gallium nitride (GaN). Further, any of a variety of semiconductor growth, formation and processing technologies can be used to form the layers and fabricate the structure or structures described herein. For example, the semiconductor layers can be formed using molecular beam epitaxy (MBE), metal organic chemical vapor deposition (MOCVD), which is also sometimes referred to as organic metallic vapor phase epitaxy (OMVPE), or any other technique. Moreover, the thicknesses of the various semiconductor layers described below are approximate, and may range to thinner or thicker than that described. Similarly, the doping levels of the doped semiconductor layers described below are relative.

The present invention is directed to a semiconductor structure that includes a bipolar device, such as a heterojunction bipolar transistor (HBT), and a p-type field effect transistor (pFET) integrated on a common substrate, referred to generally as a BiFET, and formed in a GaAs material system.

Embodiments also include a complementary BiFET (BiCFET) including a p-type FET (pFET) and an n-type FET (nFET) integrated with an HBT in a GaAs material system. The following description contains specific information pertaining to the implementation of the present invention. One skilled in the art will recognize that the present invention may be implemented in a manner different from that specifically discussed in the present application. Moreover, some of the specific details of the invention are not discussed in order not to obscure the invention.

The drawings in the present application and their accompanying detailed description are directed to merely exemplary embodiments of the invention. To maintain brevity, other embodiments of the present invention are not specifically described in the present application and are not specifically illustrated by the present drawings. Certain details and features have been left out of the drawings, which will be apparent to a person of ordinary skill in the art. Although structure **100** illustrates an exemplary BiFET comprising an NPN HBT and a pFET, which are situated over a substrate in a semiconductor die, the present invention may also apply to a BiFET comprising a PNP HBT and an nFET; an NPN HBT and both an nFET and a pFET; and a PNP HBT and both an nFET and a pFET.

FIG. 1 is a schematic diagram illustrating a cross-sectional view of an exemplary structure including an exemplary BiFET in accordance with one embodiment of the present invention. Certain details and features have been left out of FIG. 1, which are apparent to a person of ordinary skill in the art. The structure **100** includes BiFET **102**, isolation regions **110**, **112**, and **114**, and substrate **108**, which can be a semi-insulating GaAs substrate. The BiFET **102** includes an HBT **104**, which is located over substrate **108** between isolation regions **110** and **112**, and pFET **106**, which is located over substrate **108** between isolation regions **112** and **114**. Isolation regions **110**, **112**, and **114** provide electrical isolation from other devices on substrate **108** and can be formed in a manner known in the art.

The HBT **104** includes sub-collector layer **116**, a first collector layer segment **118**, a second collector layer segment **119**, an optional etch-stop layer segment **121**, a base layer segment **122**, an emitter layer segment **124**, an emitter cap layer segment **126**, a bottom contact layer segment **132**, a top contact layer segment **134**, collector contact **136**, base contacts **138**, and emitter contact **142**.

For the purpose of description herein, an emitter can include one or more parts associated with an emitter stack. In the example HBT configuration **104** of FIG. 1, such an emitter stack can include the emitter layer **124**, the emitter cap layer **126**, the bottom contact layer **132**, and the top contact layer **134**. Accordingly, an emitter as described herein can include the emitter layer **124** and/or the emitter cap layer **126**.

Also for the purpose of description herein, the example HBT topology is described in the context of GaAs/InGaP. It will be understood, however, that one or more features of the present disclosure can also be applied to other material systems used for HBTs, including, for example, indium phosphide (InP), antimonides, or nitride based materials.

The pFET **106** includes a back gate contact **113**, a lightly doped N type GaAs segment **152**, a lightly doped P type GaAs segment **154**, an optional etch stop layer segment **156**, typically comprising lightly doped N type or P type InGaP, source contact layer **158** and drain contact layer **162**, typically comprising heavily doped P type GaAs, gate contact **164**, source contact **166**, and drain contact **168**. Alternatively, the optional etch stop layer segment **156** can be undoped. In the present embodiment, the HBT **104** can be an NPN HBT integrated in

a complementary arrangement with the pFET **106**. In another embodiment, the HBT **104** can be a PNP HBT integrated with an nFET, or can be a PNP HBT or an NPN HBT integrated with the pFET **106** and with an nFET. In the present embodiment, the pFET **106** can be a depletion mode FET or an enhancement mode FET.

The sub-collector layer **116** is situated on substrate **108** and can comprise heavily doped N type GaAs. The sub-collector layer **116** can be formed by using a metal organic chemical vapor deposition (MOCVD) process or other processes. The first collector layer segment **118** and the collector contact **136** are located on the sub-collector layer **116**. The first collector layer segment **118** can comprise lightly doped N type GaAs. The second collector layer segment **119** can comprise lightly doped P type GaAs. The first collector layer segment **118** and the second collector layer segment **119** can be formed by using a MOCVD process or other processes. The collector contact **136** can comprise an appropriate metal or combination of metals, which can be deposited and patterned over the sub-collector layer **116**.

The optional etch stop layer segment **121** can be located on the second collector layer segment **119** and can comprise lightly doped N type or P type InGaP. Alternatively, the optional etch stop layer segment **121** can be undoped. The etch stop layer segment **121** can be formed by using a MOCVD process or other processes.

The base layer segment **122** is located on the etch stop layer segment **121** and can comprise heavily doped P type GaAs. The base layer segment **122** can be formed by using a MOCVD process or other processes.

The emitter layer segment **124** and base contacts **138** are located on base layer segment **122**. The emitter layer segment **124** can comprise lightly doped N type indium gallium phosphide (InGaP) and can be formed on the base layer segment **122** by using a MOCVD process or other processes. The base contacts **138** can comprise an appropriate metal or combination of metals, which can be deposited and patterned over base layer segment **122**. The emitter cap layer segment **126** is located on the emitter layer segment **124** and can comprise lightly doped N type GaAs. The emitter cap layer segment **126** can be formed by using a MOCVD process or other processes.

The bottom contact layer segment **132** is located on the emitter cap layer segment **126** and can comprise heavily doped N type GaAs. The bottom contact layer segment **132** can be formed by using a MOCVD process or other processes.

The top contact layer segment **134** is situated on the bottom contact layer segment **132** and can comprise heavily doped N type indium gallium arsenide (InGaAs). The top contact layer segment **134** can be formed by using a MOCVD process or other processes. The emitter contact **142** is located on the top contact layer segment **134** and can comprise an appropriate metal or combination of metals, which can be deposited and patterned over top contact layer segment **134**.

During operation of the HBT **104**, current flows from the emitter contact **142**, through the top contact layer segment **134**, bottom contact layer segment **132**, emitter cap layer segment **126**, emitter layer segment **124**, and into the base layer segment **122** and is indicated by arrow **137**.

To form the pFET **106** in the collector of the HBT **104**, a lightly doped P type GaAs layer segment **154** is located over a lightly doped N type GaAs layer segment **152**, which is located over a heavily doped N type GaAs layer segment **151**. A back gate contact **113** is formed on the heavily doped N type GaAs layer segment **151** to create a back gate for the pFET **106**. The back gate contact **113** can comprise an appro-

appropriate metal or combination of metals, which can be deposited and patterned over the heavily doped N type GaAs layer segment **151**.

The lightly doped N type GaAs layer segment **152** is substantially similar in composition and formation to the first collector layer segment **118** discussed above. The lightly doped P type GaAs layer segment **154** is substantially similar in composition and formation to the second collector layer segment **119** discussed above.

The lightly doped P type GaAs layer segment **154** forms the channel of the pFET **106**. The etch stop layer segment **156** is situated on the lightly doped P type GaAs layer segment **154** and can comprise lightly doped N type or P type InGaP. Alternatively, the etch stop layer segment **156** can be undoped. The etch stop layer segment **156** can be formed on the lightly doped P type GaAs layer segment **154** by using a MOCVD process or other appropriate processes. If implemented, the etch stop layer segment **156** can have a thickness between approximately 10 nanometers (nm) and approximately 15 nm. In one embodiment, the pFET **106** can be an enhancement mode FET and the etch stop layer segment **156** can have a thickness less than 10 nm.

The source contact layer **158** and the drain contact layer **162** are located on the etch stop layer segment **156** and can comprise heavily doped P type GaAs to form source and drain regions, respectively. The source and drain contact layers **158** and **162** can be formed by using a MOCVD process or other processes. A source contact **166** and drain contact **168** are located on the etch stop layer segment **156**. Source contact **166** and drain contact **168** can comprise platinum gold ("PtAu") or other appropriate metals and can be formed in a manner known in the art. A gate contact **164** is located on the etch stop layer segment **156** in gap **165**, which is formed between source and drain contact layers **158** and **162**, and can comprise an appropriate metal or combination of metals. The gap **165** can be formed by utilizing an appropriate etch chemistry to selectively etch through a layer of InGaAs and a layer of GaAs and stop on etch stop layer segment **156**. After the gap **165** has been formed, gate contact **164** can be formed on etch stop layer segment **156** in a manner known in the art. In one embodiment, the FET **106** can be an enhancement mode FET and gate contact **164** can be formed directly on the lightly doped P type GaAs layer segment **154**. In that embodiment, an appropriate etch chemistry can be utilized to selectively etch through etch stop layer segment **156** and stop on lightly doped P type GaAs layer segment **154**.

Thus, by forming the pFET **106** in the layers that comprise the collector of the HBT **104**, a pFET can be integrated with an NPN HBT, yielding a complementary BiFET.

FIG. 2 is a schematic diagram illustrating a cross-sectional view of an alternative embodiment of the structure of FIG. 1. The structure **200** shown in FIG. 2 includes a BiCFET structure that includes an HBT **204**, a pFET **206** and an nFET **207**.

Elements and structures in FIG. 2 that are similar to corresponding elements and structures in FIG. 1 will not be described again in detail, but instead, will be referred to using the nomenclature 2XX, where "XX" refers to a similar element in FIG. 1.

The BiCFET **202** includes an HBT **204** located between isolation region **210** and isolation region **212**, a pFET **206** located between isolation region **212** and **214**, and includes an nFET **207** located between isolation region **214** and isolation region **215**.

The HBT **204** includes sub-collector layer **216**, a first collector layer segment **218**, a second collector layer segment **219**, an optional etch-stop layer segment **221**, a base layer segment **222**, an emitter layer segment **224**, an emitter cap

layer segment **226**, a second optional etch stop layer **228**, a bottom contact layer segment **232**, a top contact layer segment **234**, collector contact **236**, base contacts **238**, and emitter contact **242**.

As described herein, an emitter can include one or more parts associated with an emitter stack. In the example HBT configuration **204** of FIG. 2, such an emitter stack can include the emitter layer **224**, the emitter cap layer **226**, second etch stop layer **228**, the bottom contact layer **232**, and the top contact layer **234**. Accordingly, an emitter as described herein can include the emitter layer **224** and/or the emitter cap layer **226**.

As also described herein, the example HBT topology is described in the context of GaAs/InGaP. It will be understood, however, that one or more features of the present disclosure can also be applied to other material systems used for HBTs, including, for example, indium phosphide (InP), antimonides, or nitride based materials.

The pFET **206** comprises a lightly doped P type GaAs layer segment **254** located over a lightly doped N type GaAs layer segment **252**, which is located over a heavily doped N type GaAs layer segment **251**. A back gate contact **213** is formed on the heavily doped N type GaAs layer segment **251** to create a back gate for the pFET **206**. The back gate contact **213** can comprise an appropriate metal or combination of metals, which can be deposited and patterned over the heavily doped N type GaAs layer segment **251**.

The lightly doped P type GaAs layer segment **254** forms the channel of the pFET **206**. The etch stop layer segment **256** is situated on the lightly doped P type GaAs layer segment **254** and can comprise lightly doped N type or P type InGaP. Alternatively, the optional etch stop layer segment **256** can be undoped. The etch stop layer segment **256** can be formed on the lightly doped P type GaAs layer segment **254** by using a MOCVD process or other appropriate processes. If implemented, the etch stop layer segment **256** can have a thickness between approximately 10 nanometers (nm) and approximately 15 nm. The source contact layer **258** and the drain contact layer **262** are located on the etch stop layer segment **256** and can comprise heavily doped P type GaAs to form source and drain regions, respectively. A source contact **266** and drain contact **268** are located on the etch stop layer segment **256**. A gate contact **264** is located on the etch stop layer segment **256** in gap **285**, which is formed between source and drain regions **258** and **262**, and can comprise an appropriate metal or combination of metals.

To form the nFET **207** in the layers that comprise the emitter of the HBT **104**, a lightly doped P type GaAs layer segment **255** is located over a lightly doped N type GaAs layer segment **253**, which is located over the heavily doped N type GaAs layer segment **251**. The lightly doped N type GaAs layer segment **253** is substantially similar in composition and formation to the first collector layer segment **118** discussed above. The lightly doped P type GaAs layer segment **255** is substantially similar in composition and formation to the second collector layer segment **119** discussed above.

An etch stop layer segment **257** is located on the lightly doped P type GaAs layer segment **255** and is similar to the etch stop layer segment **256**.

A heavily doped P type GaAs layer segment **259** is located on the etch stop layer segment **257** and is substantially similar in composition and formation to base layer segment **122** discussed above. A back gate contact **260** is formed on the heavily doped P type GaAs layer segment **259** to create a back gate for the nFET **207**. The back gate contact **260** can comprise an appropriate metal or combination of metals, which can be deposited and patterned over the heavily doped P type

GaAs layer segment **259**. A lightly doped N type InGaP segment **261** is located on the heavily doped P type GaAs segment **259** and is substantially similar in composition and formation to the emitter layer segment **124** discussed above.

A lightly doped N type GaAs layer segment **263** is located on the lightly doped N type InGaP layer segment **261** and is substantially similar in composition and formation to the emitter cap layer segment **126** discussed above. The lightly doped N type GaAs layer segment **263** forms a channel for the nFET **207**. The second optional etch stop layer segment **267** is located on the lightly doped N type GaAs layer segment **263** and can comprise lightly doped N type or P type InGaP. Alternatively, the second optional etch stop layer segment **267** can be undoped. The second optional etch stop layer segment **267** can be formed on the lightly doped N type GaAs layer segment **263** by using a MOCVD process or other appropriate processes. In an embodiment, the second optional etch stop layer segment **267** can have a thickness between approximately 10 nm and approximately 15 nm. In an embodiment, the nFET **207** can be an enhancement mode FET and the etch stop layer segment **267** can have a thickness less than 10 nm.

A source region **269** and drain region **271** are located on the second optional etch stop layer segment **267** and can comprise heavily doped N type GaAs. The source region **269** and the drain region **271** can be formed by using a MOCVD process or other processes. Contact layer segments **273** and **275** are located on source and drain regions **269** and **271**, respectively, and can comprise heavily doped N type InGaAs. Contact layer segments **273** and **275** can be formed by using a MOCVD process or other processes.

A source contact **277** and a drain contact **279** are located on top contact layer segments **271** and **273**, respectively. A gate contact **281** is located on the second optional etch stop layer segment **267** in gap **285**. Gap **285** can be formed by utilizing an appropriate etch chemistry to selectively etch through a layer of InGaAs and a layer of GaAs and stop on second optional etch stop layer segment **267**. After gap **285** has been formed, gate contact **281** can be formed on the second optional etch stop layer segment **267** in a manner known in the art. In an embodiment, the nFET **207** can be an enhancement mode FET and gate contact **281** can be formed directly on lightly doped N type GaAs layer segment **263**. In that embodiment, an appropriate etch chemistry can be utilized to selectively etch through the second optional etch stop layer segment **267** and stop on lightly doped N type GaAs layer segment **263**.

Accordingly, a BiCFET can be fabricated that includes complementary pFET **206** and nFET **207**, formed on a GaAs substrate along with either an NPN or a PNP HBT.

In some embodiments as described herein, some or all of the etch stop layers (e.g., **121**, **156**, **221**, **228**, **256**, **257** and **267**) can include indium gallium phosphide (InGaP) or indium gallium arsenide (InGaAs). Such an etch stop layer can have a thickness range between 10 nanometers (nm) and 15 nm. Other thickness ranges can also be implemented. In some embodiments, some or all of the foregoing etch stop layers can include any material with etch selectivity to, for example, a channel of an FET. Such a material can be implemented in an appropriate thickness or within an appropriate range of thicknesses so as to achieve similar results as the foregoing example materials InGaP or InGaAs.

FIG. 3 shows a process **300** that can be implemented to fabricate the example BiFET **102** of FIG. 1 or a portion of the example BiCFET **202** of FIG. 2. In block **302**, a semiconductor substrate can be provided. In some embodiments, such a semiconductor layer can include one or more layers disclosed

herein, including a semi-insulating GaAs layer such as the example layers **108** and **208** of FIGS. 1 and 2. In block **304**, a heterojunction bipolar transistor (HBT) can be formed so as to include a collector layer disposed over the substrate. In some embodiments, such a collector layer can include one or more layers disclosed herein, including a p- GaAs layer (**119** in FIG. 1 and **219** in FIG. 2). In block **306**, a field effect transistor (FET) can be formed so as to include a channel region disposed over the substrate and formed from the same material as the collector layer of the HBT. In some embodiments, such a channel region can include one or more layers disclosed herein, including the p- GaAs layer (**154** in FIG. 1 and **254** in FIG. 2). In some implementations, other structures associated with the HBT (e.g., base, emitter and contacts) and the FET (e.g., source, drain and contacts) can be formed.

FIG. 4 shows a process **310** that can be implemented to fabricate the example BiCFET **202** of FIG. 2. In block **312**, a semiconductor substrate can be provided. In some embodiments, such a semiconductor layer can include one or more layers disclosed herein, including a semi-insulating GaAs layer such as the example layer **208** of FIG. 2. In block **314**, a sub-collector layer can be formed over the substrate layer. In some embodiments, such a sub-collector layer can include one or more layers disclosed herein, including the n+ GaAs layer (**216** and/or **251** in FIG. 2). In block **316**, an HBT can be formed over the sub-collector layer. In some embodiments, such an HBT can be formed so as to include the example layers described herein in reference to FIG. 2, including a collector **219** (e.g., p- GaAs), a base **222** (e.g., p+ GaAs), an emitter **224** (e.g., n- InGaP), and an emitter cap **226** (e.g., n- GaAs). In block **318**, a first FET can be formed over the sub-collector layer, so that its channel region is formed from same material as the HBT's collector region. In some embodiments, such a first FET can be formed so as to include the example layers described herein in reference to FIG. 2, including a channel layer **254** (e.g., p- GaAs), a source contact layer **258** (e.g., p+ GaAs), and a drain contact layer **262** (e.g., p+ GaAs). In block **320**, a second FET can be formed over the sub-collector layer, so that its channel region is formed from same material as the HBT's emitter cap region. In some embodiments, such a second FET can be formed so as to include the example layers described herein in reference to FIG. 2, including a channel layer **263** (e.g., n- GaAs), a source contact layer **269** (e.g., n+ GaAs), and a drain contact layer **271** (e.g., n+ GaAs).

FIGS. 5-7 show processes that can be more specific examples of the processes described in reference to FIGS. 3 and 4, in the context of the example configurations of FIGS. 1 and 2. FIG. 5 shows a process **330** that can be implemented to fabricate an HBT such as those of FIGS. 1 and 2. FIG. 6 shows a process **350** that can be implemented to fabricate an FET such as those of FIGS. 1 and 2. FIG. 7 shows a process **360** that can be implemented to fabricate a second FET such as that of FIG. 2. For the purpose of description of FIGS. 5-7, it will be assumed that a semiconductor substrate (such as semi-insulating GaAs) and a sub-collector layer (such as n+ GaAs) are provided.

The example processes **330**, **350** and **360** can be performed in sequence, in parallel where applicable, or in any combination thereof. Examples of such schemes of integrating an HBT with one or more FETs are described herein in greater detail.

In the example process **330** of FIG. 5 where an HBT is being fabricated, a first collector layer (e.g., n- GaAs) can be formed on the sub-collector layer in block **332**. In block **334**, a second collector layer (e.g., p- GaAs) can be formed on the first collector layer. In block **336**, a first etch stop layer (e.g.,

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n- or p- InGaP) can be formed on the second collector layer. In block 338, a base layer (e.g., p+ GaAs) can be formed on the first etch stop layer. In block 340, an emitter layer (e.g., n- InGaP) can be formed on the base layer. In block 342, an emitter cap layer (e.g., n- GaAs) can be formed on the emitter layer. In block 344, a second etch stop layer (e.g., n- or p- InGaP) can be formed on the emitter cap layer. In block 346, a bottom contact layer (e.g., n+ GaAs) for the emitter can be formed on the second etch stop layer. In block 348, a top contact layer (e.g., InGaAs) for the emitter can be formed on the bottom contact layer. In block 349, contacts for the emitter, base and collector can be formed so as to yield HBT configurations such as those (104, 204) of FIGS. 1 and 2.

In the example process 350 of FIG. 6 where a first FET (e.g., a pFET) is being fabricated, a doped layer (e.g., n- GaAs) can be formed on the sub-collector layer in block 352. In block 354, a channel layer (e.g., p- GaAs) can be formed on the doped layer. In block 356, a first etch stop layer (e.g., n- or p- InGaP) can be formed on the channel layer. In block 358, source and drain contact layers (e.g., p+ GaAs) can be formed on the first etch stop layer. In block 359, contacts for the source, drain, gate and back gate can be formed so as to yield FET configurations such as the example pFETs 106 and 206 of FIGS. 1 and 2.

In the example process 360 of FIG. 7 where a second FET (e.g., an nFET) is being fabricated, a first doped layer (e.g., n- GaAs) can be formed on the sub-collector layer in block 362. In block 364, a second doped layer (e.g., p- GaAs) can be formed on the first doped layer. In block 366, a first etch stop layer (e.g., n- or p- InGaP) can be formed on the second doped layer. In block 368, a third doped layer (e.g., p+ GaAs) can be formed on the first etch stop layer. In block 370, a fourth doped layer (e.g., n- InGaP) can be formed on the third doped layer. In block 372, a channel layer (e.g., n- GaAs) can be formed on the fourth doped layer. In block 374, a second etch stop layer (e.g., n- or p- InGaP) can be formed on the channel layer. In block 376, source and drain regions (e.g., n+ GaAs) can be formed on the second etch stop layer. In block 378, source and drain contact layer (e.g., InGaAs) can be formed on the source and drain regions. In block 379, contacts for the source, drain, gate and back gate can be formed so as to yield an FET configuration such as the example nFET (207) of FIG. 2.

In some implementations, the foregoing integration of an HBT with one or more FETs can be achieved in a number of ways, including a re-growth methodology, a two-step methodology, and/or a co-integration methodology. In the re-growth methodology, re-growth can involve a selective area, multilayer, and/or pre-patterned multilayer techniques. The selected area technique can include growing one device, etching in one or more selected areas, and then growing the other device in those selected area(s). The multilayer technique can include a single growth run, with the device layers stacked, not merged or shared. The pre-patterned multi-layer technique can include selective etching of a substrate prior to depositing layers for two or more devices.

In the two-step growth methodology, one device can be formed first, followed by formation of the other device adjacent to the first device. In the context of integration of three devices (such as the example of FIG. 2), such a two-step growth can be extended to include a third step growth of the third device.

In the co-integration methodology, a single growth can yield layers that are shared by two or more devices. In some implementations, the co-integration methodology can include single growth generated layers that constitute a majority of the layers of the two or more devices.

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FIG. 8 shows that in some embodiments, one or more features associated with the BiFET and/or BiCFET configurations described herein can be implemented as part of a semiconductor die 400. For example, such a die can include a power amplifier (PA) circuit 402 having one or more BiFET and/or BiCFET devices 404. Such a PA circuit 402 can be configured so as to amplify an input RF signal (RF_IN) to generate as an amplified output RF signal (RF_OUT).

FIG. 9 shows another example die 410 that includes a PA circuit 412 controlled by a PA/Switch controller 414. The controller 414 can be configured to include one or more BiFET and/or BiCFET devices 404.

FIG. 10 shows that in some embodiments, a die (such as the example die 410 of FIG. 9) can be implemented in a packaged module 420. The die 410 can include a PA 412 and a controller 414 having a BiFET (and/or BiCFET) 404 having one or more features as described herein. Such a module can further include one or more connections 422 configured to facilitate passage of signals and/or power to and from the die 410. Such a module can further include one or more packaging structures 424 that provide functionalities such as protection (e.g., physical, electromagnetic shielding, etc.) for the die 410.

FIG. 11 shows that in some embodiments, a component such as the die 410 of FIG. 9 or the module 420 of FIG. 10 can be included in a wireless device 430 such as a cellular phone, a smart phone, etc. In FIG. 11, a packaged RF module 420 is depicted as being part of the wireless device 430; and such a module is shown to include a BiFET and/or BiCFET 404 having one or more features as described herein. In some embodiments, an unpackaged die having similar functionality can also be utilized to achieve similar functionalities. The wireless device 430 is depicted as including other common components such as an RFIC 434 and an antenna 436. The wireless device 436 can also be configured to receive a power source such as a battery 432.

While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible that are within the scope of the invention. For example, the invention is not limited to the gallium arsenide material system.

What is claimed is:

1. A semiconductor structure, comprising:

- a heterojunction bipolar transistor (HBT) including first and second collector layers located over a substrate, the first collector layer including a p-type semiconductor material, the second collector layer including an n-type semiconductor material and located between the substrate and the first collector layer; and
- a p-type field effect transistor (FET) located over the substrate, the FET including a channel corresponding to a first semiconductor portion formed in the semiconductor material that forms the first collector layer of the HBT and further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer, an etch stop layer segment being located over the first collector layer of the HBT and the channel of the FET, between a base layer of the HBT and the first collector layer.

2. The semiconductor structure of claim 1 wherein the semiconductor material that forms the first collector layer of the HBT and the channel of the FET includes p-type gallium arsenide.

3. The semiconductor structure of claim 1 wherein the etch stop layer includes a material with etch selectivity to the channel of the FET.

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4. The semiconductor structure of claim 1 wherein the etch stop layer includes indium gallium arsenide or indium gallium phosphide.

5. The semiconductor structure of claim 4 wherein the etch stop layer has a thickness range between 10 nanometers (nm) and 15 nm.

6. A semiconductor structure, comprising:

a heterojunction bipolar transistor (HBT) including first and second collector layers located over a substrate and an emitter stack located over the substrate, the first collector layer including a p-type semiconductor material the second collector layer including an n-type semiconductor material and located between the substrate and the first collector layer, the emitter stack including an n-type semiconductor material;

a first field effect transistor (FET) located over the substrate, the first FET being a p-type transistor including a channel corresponding to a first semiconductor portion formed in the p-type semiconductor material that forms the first collector layer of the HBT, and further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer of the HBT; and

a second field effect transistor (FET) located over the substrate, the second FET being an n-type transistor including a channel formed in the n-type semiconductor material of the emitter stack of the HBT, a first etch stop layer segment being located over the collector layers of the HBT and the channel of the first FET, between a base layer of the HBT and the first collector layer, and a second etch stop layer segment that is part of the emitter stack of the HBT being located over the channel of the second FET.

7. The semiconductor structure of claim 6 wherein the p-type semiconductor material that forms the first collector layer of the HBT and the channel of the first FET includes p-type gallium arsenide, and the n-type semiconductor material of the emitter stack of the HBT and the channel of the second FET includes n-type gallium arsenide.

8. The semiconductor structure of claim 1 wherein the first etch stop layer segment and the second etch stop layer segment include a material with etch selectivity to the channels of the first and second FETs.

9. The semiconductor structure of claim 1 wherein the first etch stop layer segment and the second etch stop layer segment include indium gallium arsenide or indium gallium phosphide.

10. The semiconductor structure of claim 9 wherein the first etch stop layer segment and the second etch stop layer segment have a thickness range between 10 nanometers (nm) and 15 nm.

11. A method, comprising:

forming a heterojunction bipolar transistor (HBT) including first and second collector layers located over a substrate and an emitter stack located over the substrate, the first collector layer including a p-type semiconductor material, the second collector layer including an n-type semiconductor material and located between the substrate and the first collector layer, the emitter stack including an n-type semiconductor material;

forming a first field effect transistor (FET) over the substrate, the first FET being a p-type transistor including a channel formed in the p-type semiconductor material that forms the first collector layer of the HBT;

forming a second field effect transistor (FET) over the substrate, the second FET being an n-type transistor including a channel corresponding to a first semiconductor

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portion formed in the n-type semiconductor material that forms the emitter stack of the HBT and further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer;

forming a first etch stop layer segment over the collector layers of the HBT and the channel of the first FET, between a base layer of the HBT and the first collector layer; and

forming a second etch stop layer segment that is part of the emitter stack of the HBT and is over the channel of the second FET.

12. The method of claim 11 wherein the p-type semiconductor material that forms the first collector layer of the HBT and the channel of the first FET includes p-type gallium arsenide, and the n-type semiconductor material of the emitter stack of the HBT and the channel of the second FET includes n-type gallium arsenide.

13. The method of claim 11 wherein the first etch stop layer segment and the second etch stop layer segment include a material with etch selectivity to the channels of the first and second FETs.

14. The method of claim 11 wherein the first etch stop layer segment and the second etch stop layer segment include indium gallium arsenide or indium gallium phosphide.

15. The method of claim 14 wherein the first etch stop layer segment and the second etch stop layer segment have a thickness range between 10 nanometers (nm) and 15 nm.

16. A method, comprising:

forming a heterojunction bipolar transistor (HBT) including first and second collector layers located over a substrate, the first collector layer including a p-type semiconductor material, the second collector layer including an n-type semiconductor material and located between the substrate and the first collector layer;

forming a p-type field effect transistor (FET) located over the substrate, the FET including a channel corresponding to a first semiconductor portion formed in the semiconductor material that forms the first collector layer of the HBT and further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer; and

forming an etch stop layer segment over the first collector layer of the HBT and the channel of the FET, between a base layer of the HBT and the first collector layer.

17. The method of claim 16 wherein the semiconductor material that forms the first collector layer of the HBT and the channel of the FET includes p-type gallium arsenide.

18. The method of claim 16 wherein the etch stop layer includes a material with etch selectivity to the channel of the FET.

19. The method of claim 16 wherein the etch stop layer includes indium gallium arsenide or indium gallium phosphide.

20. The method of claim 19 wherein the etch stop layer has a thickness range between 10 nanometers (nm) and 15 nm.

21. A die having an integrated circuit (IC), the die comprising:

a circuit configured to process radiofrequency (RF) signal; and

an assembly of a heterojunction bipolar transistor (HBT) and a p-type field effect transistor (FET) configured to facilitate operation of the circuit, the HBT including first and second collector layers located over a substrate, the first collector layer including a p-type semiconductor material, the second collector layer including an n-type semiconductor material and located between the sub-

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strate and the first collector layer, the FET including a channel corresponding to a first semiconductor portion located over the substrate and formed in the semiconductor material that forms the first collector layer of the HBT, the FET further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer, an etch stop layer segment being located over the first collector layer of the HBT and the channel of the FET, between a base layer of the HBT and the first collector layer.

22. The die of claim 21 wherein the circuit configured to process RF signal includes a power amplifier circuit, a controller circuit for the power amplifier circuit, or a controller for a switching circuit.

23. The die of claim 21 wherein the assembly further includes a second FET having a channel located over the substrate and formed in same semiconductor material as an emitter of the HBT.

24. The die of claim 23 wherein the first FET includes a pFET.

25. The die of claim 24 wherein the second FET includes an nFET.

26. The die of claim 21 wherein the substrate includes gallium arsenide (GaAs).

27. A packaged module for a radiofrequency (RF) device, the module comprising:

a packaging substrate;

an integrated circuit (IC) formed on a die and mounted on the packaging substrate, the IC including an assembly of a heterojunction bipolar transistor (HBT) and a p-type field effect transistor (FET) configured to facilitate operation of the IC, the HBT including first and second collector layers located over a die substrate, the first collector layer including a p-type semiconductor material, the second collector layer including an n-type semiconductor material and located between the substrate and the first collector layer, the FET including a channel corresponding to a first semiconductor portion located over the die substrate and formed in the semiconductor material that forms the first collector layer of the HBT and further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer, the IC further including an etch stop layer segment located over the first collector layer of the HBT and the channel of the FET, between a base layer of the HBT and the first collector layer; and

one or more connections configured to facilitate transfer of power to the IC and RF signals to and from the IC.

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28. The packaged module of claim 27 wherein the assembly further includes a second FET having a channel located over the die substrate and formed in same semiconductor material as an emitter of the HBT.

29. The packaged module of claim 28 wherein the first FET includes a pFET and the second FET includes an nFET.

30. A wireless device, comprising:

an antenna;

a radiofrequency integrated circuit (RFIC) configured to process RF signals received from the antenna and for transmission through the antenna; and

a power amplifier (PA) circuit configured to amplify the RF signals, the PA circuit including an assembly of a heterojunction bipolar transistor (HBT) and a p-type field effect transistor (FET), the HBT including first and second collector layers located over a substrate, the first collector layer including a p-type semiconductor material, the second collector layer including an n-type semiconductor material and located between the substrate and the first collector layer, the FET including a channel corresponding to a first semiconductor portion located over the substrate and formed in the semiconductor material that forms the first collector layer of the HBT and further including a second semiconductor portion formed in the semiconductor material that forms the second collector layer, the assembly further including an etch stop layer segment located over the first collector layer of the HBT and the channel of the FET, between a base layer of the HBT and the first collector layer.

31. The wireless device of claim 30 wherein the PA is configured to operate as a high power BiFET amplifier capable of operating at a lower reference voltage than that of a bipolar transistor PA.

32. The wireless device of claim 31 wherein the substrate includes gallium arsenide (GaAs).

33. The semiconductor structure of claim 1 wherein the HBT further includes a sub-collector layer located under the first and second collector layers of the HBT and over the substrate, and the FET further includes an n-type layer located over the substrate, under the channel of the FET, and formed in the semiconductor material that forms the sub-collector layer of the HBT.

34. The semiconductor structure of claim 6 wherein the HBT further includes a sub-collector layer located under the first and second collector layers of the HBT and over the substrate, and the first FET further includes an n-type layer located over the substrate, under the channel of the first FET, and formed in the semiconductor material that forms the sub-collector layer of the HBT.

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